~~X-641~~-68-492
PREPRINT
NASA TM X- 63421

PREDICTIONS OF EXTRAGALACTIC GAMMA-RAY FLUXES BETWEEN 1 AND 100 MeV

F. W. STECKER
JOSEPH SILK

DECEMBER 1968

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-641-68-492
PREPRINT

PREDICTIONS OF EXTRAGALACTIC GAMMA-RAY FLUXES BETWEEN 1 AND 100 MEV

F. W. Stecker
Theoretical Studies Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland

and

Joseph Silk
Institute of Theoretical Astronomy
Cambridge, England

December 1968

Goddard Space Flight Center
Greenbelt, Maryland

PREDICTIONS OF EXTRAGALACTIC GAMMA-RAY FLUXES BETWEEN 1 AND 100 MEV

F. W. Stecker*
Theoretical Studies Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland

and

Joseph Silk
Institute of Theoretical Astronomy
Cambridge, England

ABSTRACT

The observed isotropic cosmic X- and gamma-rays may be produced by some combination of four possible types of extragalactic interactions. We show here that spectra from these interactions have important distinguishing characteristics in the 1-100 MeV energy range. By normalizing the theoretical spectra to the observed intensities, we have determined theoretical intensities of metagalactic cosmic-ray protons and electrons needed to account for the observed radiation.

*Research performed in part while NASA-National Research Council Resident Research Associate

PREDICTIONS OF EXTRAGALACTIC GAMMA-RAY FLUXES BETWEEN 1 AND 100 MEV

I. INTRODUCTION

Recent theoretical studies have indicated the necessity for observations of isotropic cosmic-gamma-radiation in the 1-100 MeV energy region. Such observations will enable us to determine the relative importance of the various processes which may produce the observed isotropic X-radiation below 1 MeV and gamma-radiation above 100 MeV. The first process to be examined as a possible explanation for the radiation below 1 MeV was that of Compton interactions between metagalactic cosmic-ray electrons and photons of the universal microwave radiation field.[1-4] Recently, additional processes which may be of importance in producing extragalactic gamma-radiation have been discussed by the authors. These processes are cosmic-ray electron bremsstrahlung with intergalactic matter,[5] collisions of cosmic-ray nuclei with intergalactic matter which result in the production of pi-mesons[6,7] and the mutual annihilation of matter and antimatter on possible boundary regions of baryon inhomogeneity in the universe.[8] The purpose of this paper is to discuss some implications of the results of these studies in distinguishing the gamma-ray spectra produced by these various processes and placing upper limits on the metagalactic cosmic-ray electron and nuclear fluxes. In particular, these results indicate that observational studies of isotropic gamma-radiation between 1 and 100 MeV are

critical for determining the dominant gamma-ray-producing processes in the metagalaxy and their cosmological implications.

II. CALCULATION OF GAMMA-RAY SPECTRA

For the purpose of this paper, we wish to point out the similarities in the determination of gamma-ray spectra from the various processes mentioned above. Three of these processes involve collisions between high energy cosmic-rays and an ambient gas with the various components listed in Table I.

Table I

Collisional Gamma-Ray-Producing Processes

Process	Primary Particles	Primary Ambient Gas
1. Compton	electrons	blackbody microwave photons
2. Bremsstrahlung	electrons	intergalactic hydrogen
3. Inelastic Strong Interactions	protons	intergalactic hydrogen nuclei

The fourth process, annihilation, also involves the interaction of two components, viz. ambient matter and ambient antimatter.

The gamma-ray fluxes from the processes given in Table I may be determined by evaluating a general integral of the form

$$I(E_\gamma) = c H_o^{-1} n_o \int_o^{z_{max}} dz\, (1+z)^{-\alpha} \frac{I(z)}{I_g} G_g [(1+z)E_\gamma] \tag{1}$$

where $cH_o^{-1} = 10^{28}$ cm, z is the cosmological redshift, n_o is the ambient gas density at z = 0, I(z) is the flux of cosmic-ray electrons (or protons) at redshift z, I_g is the flux of this cosmic-ray component in the galaxy and $G_g(E_\gamma)$ is defined as the local (non-redshifted) gamma-ray spectrum generated by the galactic cosmic-ray flux, I_g, in travelling through a thickness of 1 particle per cm^2 in the ambient medium. (For example, in the case of inelastic strong interactions, $G_g(E_\gamma)$ is the same as the quantity $I(E_\gamma)/nL$ calculated previously by one of the authors[9,10] The upper limit of the integration, z_{max}, is defined as the redshift corresponding to the epoch when the metagalactic cosmic-ray flux first came into existence. The exponent, α, is determined by the cosmological model taken and is found to equal 2.5 for an Einstein-de Sitter universe and 2 for a low density universe.[5-7] These cases approximate the limits of a closed universe and a universe with mean density comparable to the lower limit derived by Oort.[11]

In the case of matter antimatter annhilation, the integration is carried out over the product of interacting matter and antimatter densities instead of the product of a cosmic-ray flux and a gas density. The other difference in the treatment of annihilation radiation is that z_{max} for the annihilation case is of the order of 10^{12}, corresponding to the epoch when matter and antimatter were in equilibrium with the radiation field whereas for the other cases, z_{max}, is restricted to values $\lesssim 100$ (see Reference 7).

III. RESULTANT GAMMA-RAY SPECTRA

The resultant gamma-ray spectra from bremsstrahlung and inelastic strong interactions have been calculated for two cosmological models (viz., an Einstein-de Sitter (flat) universe with $n_0 = 10^{-5}$ cm^{-3} and an open universe with $n_0 = 10^{-7}$ cm^{-3}) and three models of cosmic ray production (viz., a burst model where all the cosmic rays were produced at some initial epoch, a constant leakage model where cosmic-rays have leaked out of radio sources at a constant rate since $t(z_{max})$, and an evolving source model as suggested by Longair[12] where the cosmic-ray production rate varies as $(1 + z)^3$). These models have been discussed previously in References 6 and 7. The annihilation gamma-ray spectra have been discussed for flat and open universes in Reference 8. The characteristics of the gamma-ray spectra from these various processes are outlined in Table II. Figure 1 illustrates the types of gamma-ray spectra which fit the present observational data.

The relativistic bremsstrahlung results are presented here for the first time and require some discussion. We have investigated two types of metagalactic cosmic-ray electron spectra. In one case, we assumed that the metagalactic electron source spectrum above 1 MeV had the same power law form ($\sim E_c^{-1.6}$) as the observed galactic spectrum and that the spectrum would steepen to $E_c^{-2.6}$ at a critical energy given by

$$E_c = 8.3\ (1 + z)^{-\alpha/2}\ \text{MeV} \tag{2}$$

due to Compton collisions with the universal blackbody radiation. It was found that the cosmic-ray electron flux needed in this case would be in all cases greater than the observed galactic value of $1.1 \times 10^{-3} E_e^{-1.6}$ cm^{-2} sec^{-1} sr^{-1} GeV^{-1} in order to produce the observed X-radiation. For the second case, we considered a power law spectrum with an exponent of 2.6 as observed for galactic electrons above 2 GeV together with the hypothesis that the true galactic spectrum is given by an extrapolation of this power law[13] to lower energies, i.e., $1.26 \times 10^{-2} E_e^{2.5}$. Again, we have considered steepening due to Compton collisions. The bremsstrahlung gamma-ray spectrum is then given by[14]

$$I(z)\, G_{g,b}(E_\gamma, z) = 3 \times 10^{-26} \frac{\int_{E_\gamma}^{\infty} dE_e\, I(E_e, z)}{E_\gamma} \tag{3}$$

where $I_e(E_e)$ is the differential electron energy spectrum.

IV. METAGALACTIC COSMIC-RAY FLUXES IMPLIED BY PRESENT OBSERVATIONS

By calculating the gamma-ray spectrum produced by metagalactic strong interactions, it becomes possible to make use of the recent observations made by the OSO-3 gamma-ray telescope[16] to place limits on the metagalactic flux of cosmic-ray protons, as has been done by one of us in Reference 6. Similarly, one may use the bremsstrahlung calculations (assuming a galactic electron spectrum of the form 1.26×10^{-2} $E^{-2.6}$ cm^{-2} sec^{-1} sr^{-1} GeV^{-1}) to calculate the flux of metagalactic electrons needed to produce the observed X-ray flux in

Table II

Characteristics of Predicted Extragalactic Gamma-Ray Spectra from Various Processes in Given Energy Regions

	0.1–1 MeV	1–100 MeV	>100 MeV
Compton	Power law spectrum of form $E^{-\Gamma}$ where $\Gamma = (\beta + 1)/2$ and β is the index of the cosmic-ray electron spectrum. In particular $\Gamma = 2.3$ for $\beta = 3.6$ as discussed by Felten and Morrison.[15]	$\sim E^{-2.3}$	$\sim E^{-2.3}$
Bremsstrahlung	Power law spectrum of form $E^{-\Gamma}$ where $\Gamma = \beta$ and $\beta \simeq 2.6$ in an open universe (see Reference 5 for details.)	Power law spectrum of form $E^{-\Gamma}$ where $\Gamma = \beta$ and $\beta \simeq 3.6$ (see text).	$\sim E^{-3.6}$
Inelastic Strong Interactions	Negligible contribution; power law of form $\sim E^{+\Gamma}$ where $\Gamma \simeq 3$	Spectrum peaks in this energy region at $\simeq \frac{70\ \text{MeV}}{(1 + z_{max})}$	$\sim E^{-3}$
Annihilation	Power law of form $E^{-\Gamma}$ where $\Gamma \simeq 1.5$ for flat universe and $\Gamma = 2.0$ for open universe.		Power law becomes steeply falling spectrum with no flux above 865 MeV

the vicinity of 1 MeV. Referring to the local metagalactic cosmic-ray flux ($z \simeq 0$) as I_o and the galactic cosmic-ray flux as I_g, we have plotted in Figures 2 and 3 the values of $\log_{10} (I_o/I_g)$ versus $\log_{10} (1 + z_{max})$ needed in each case to explain the observations.

We hope that the experiments now being developed by various gamma-ray astronomy groups to investigate the 1-100 MeV energy region, will soon allow us to choose the mechanism, or combination of mechanisms of gamma-ray production which predominate in the metagalaxy. When this determination has been made we stand to gain valuable information in the fields of cosmology, cosmogony and cosmic-ray astronomy.

REFERENCES

1. Hoyle, F., Phys. Rev. Letters 15, 131 (1965)

2. Gould, R. J., Phys. Rev. Letters 15, 511 (1965)

3. Fazio, G. G., Stecker, F. W. and Wright, J. P. ApJ. 144, 611 (1966)

4. Felten, J. E., Phys. Rev. Letters 15, 1003 (1965)

5. Silk, J., and McCray, R., to be published

6. Stecker, F. W., Nature 220, 675 (1968)

7. Stecker, F. W., to be published

8. Stecker, F. W., Nature, in press

9. Stecker, F. W., Smithsonian Astrophys. Obs. Sp. Rpt. No. 260 (1967)

10. Stecker, F. W. Tsuruta, S. and Fazio, G. G., ApJ. 151, 881 (1968)

11. Oort, J. H., 11th Solvay Conf. Brussels: Stoops, pg. 180 (1958)

12. Longair, M. S., Mon. Not. R. Ast. Soc. 133, 421 (1966)

13. Tanaka, Y., Can. Jour. Phys. 46, S536 (1968)

14. Ginzburg, V. L., and Syrovatskii, S. I., The Origin of Cosmic Rays, Macmillan Co., New York (1964)

15. Felten, J. E., and Morrison, P., ApJ. 146, 686 (1966)

16. Clark, G. W., Garmire, G. P., and Kraushaar, W. L., ApJ. Letters 153, L203, (1968)

17. Metzger, A. E., Anderson, E. C., van Dilla, M. A., and Arnold, J. R., Nature 204, 766 (1964)

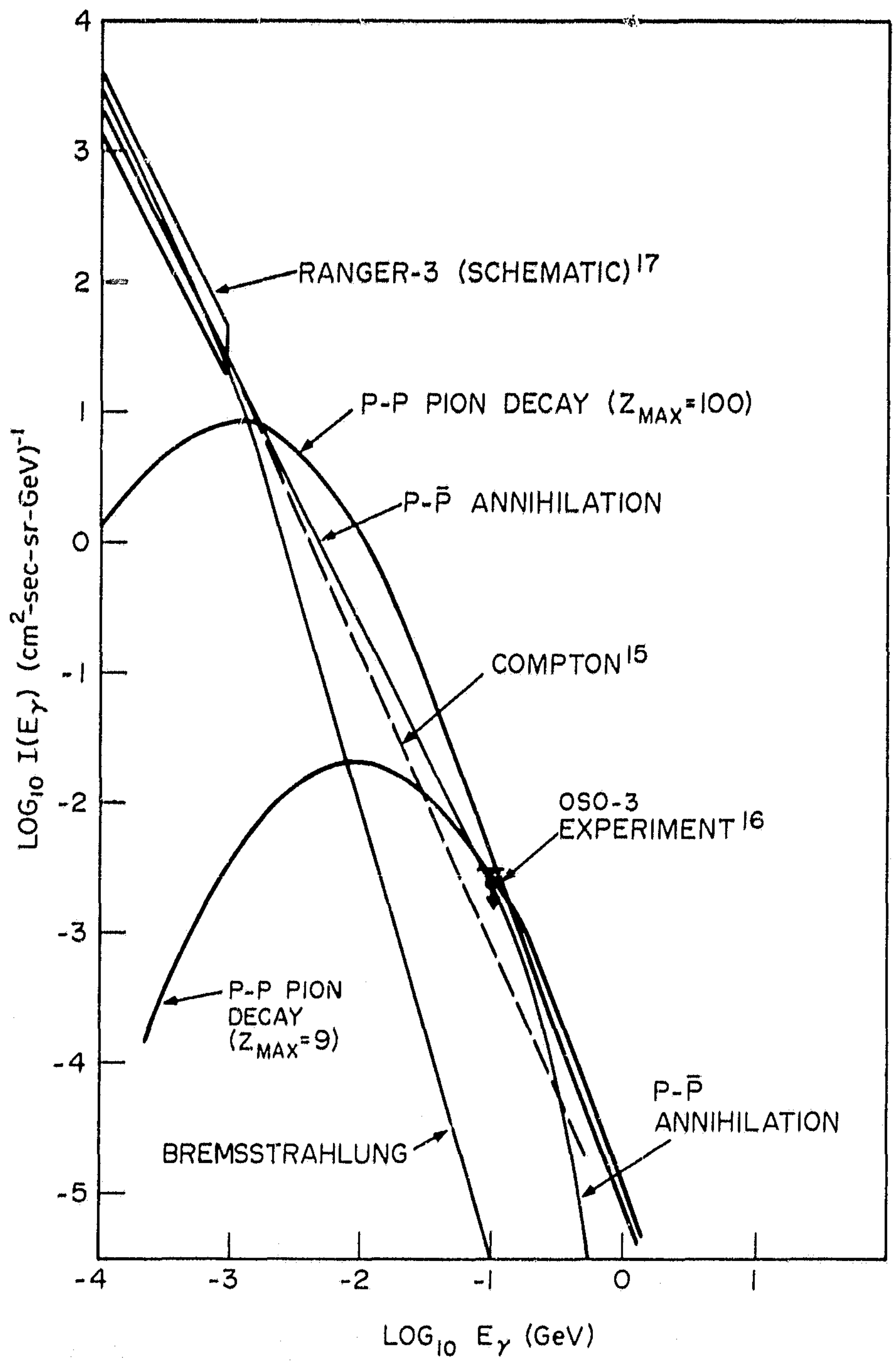

Figure 1–Observed and Predicted Forms of Extragalactic Gamma-Ray Spectra

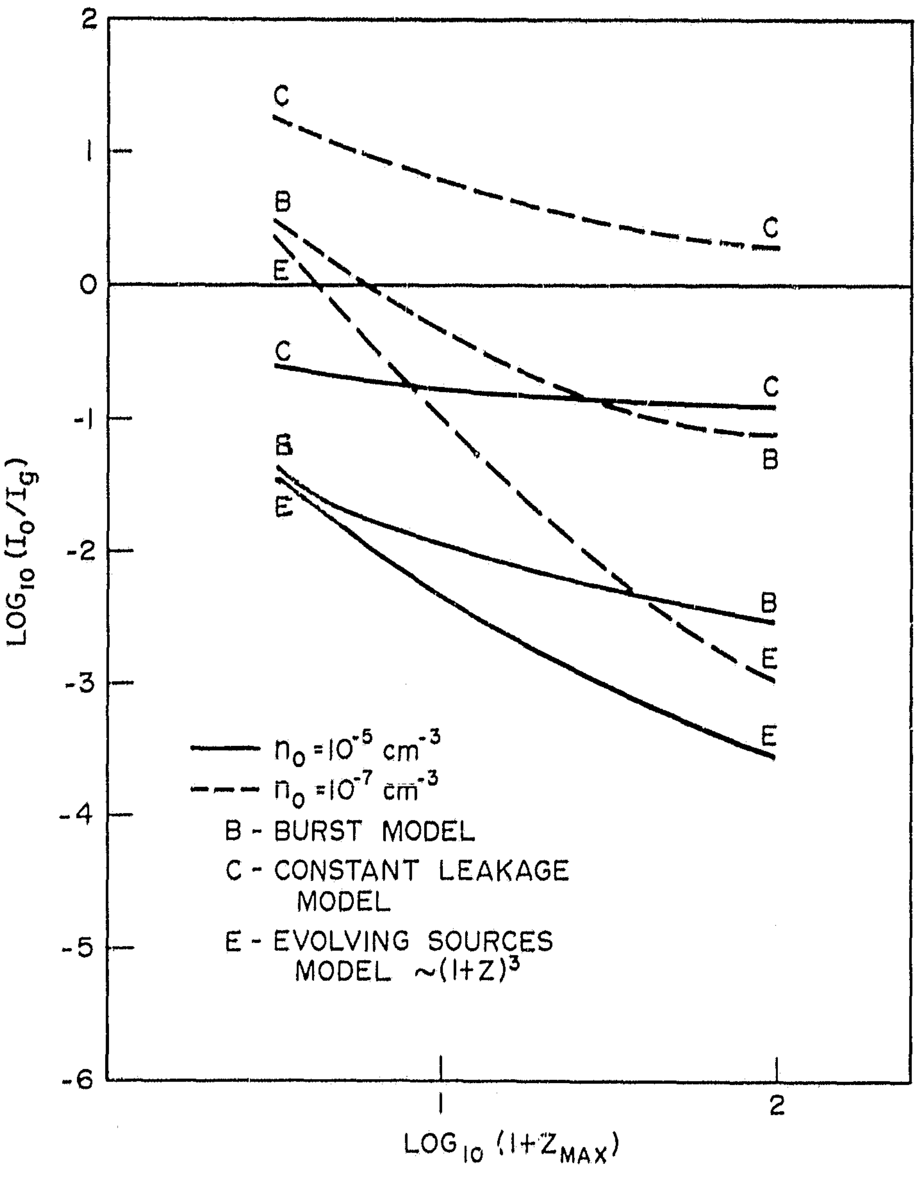

Figure 2—Metagalactic Proton Intensity Upper Limits

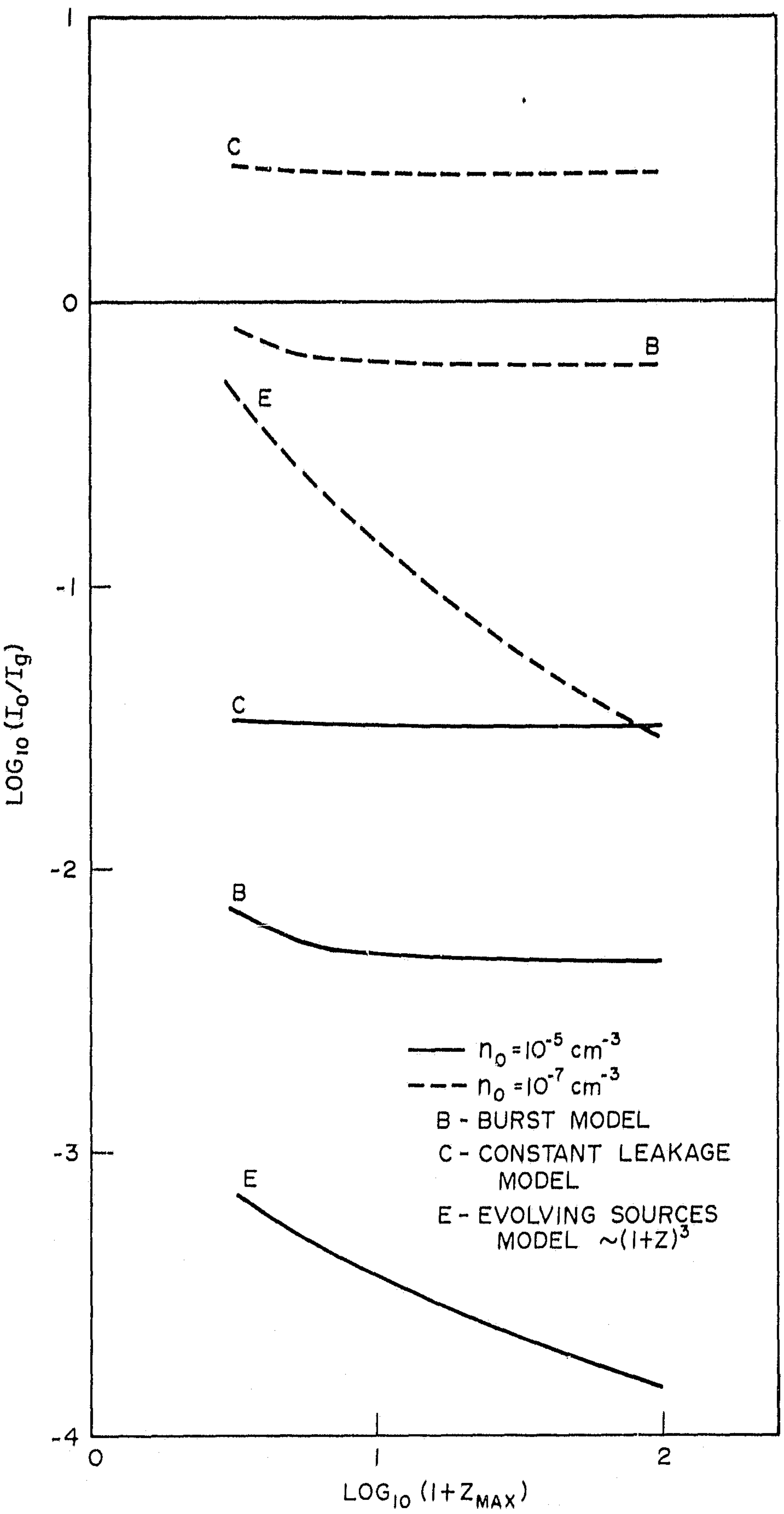

Figure 3–Metagalactic Electron Intensity